

A FUZZY LOGIC BASED RECOGNITION TECHNIQUE FOR POWER QUALITY CATEGORIZATION

A. Thapar
alok@itee.uq.edu.au

T. K. Saha
saha@itee.uq.edu.au

Z. Y. Dong
zdong@itee.uq.edu.au

School of Information Technology & Electrical Engineering
The University of Queensland Australia

Abstract

With an increasing usage of sensitive electronic equipment power quality has become a major concern now. One critical aspect of power quality studies is the ability to perform automatic power quality data analysis and categorization. The objective of this paper is to present a technique based on fuzzy logic to categorize power quality events. Inherent features are extracted from recorded waveforms using Fourier and wavelet analyses and fed into a fuzzy expert system. The categorization technique has been implemented using the Fourier, Wavelet and Fuzzy Logic Toolboxes in MATLAB and tested with real power quality data. The findings are reported in this paper.

Key words: power quality, wavelet transform, Fourier transforms, fuzzy logic

1. INTRODUCTION

Any variation in voltage, current, or frequency which may lead to an equipment failure or malfunction is potentially a Power Quality problem [1]. The classification and identification of power disturbances are governed by certain standards. The major cause of the problem is the increase in non-linear loads, which distort current and voltage waveforms. Modern electronic equipment is much more sensitive to such disturbances than traditional loads (lighting and motors) [2, 3]. The result is that the processes are interrupted, productivity is halted, and millions of dollars are lost. To avoid this, the disturbances need to be first categorized so that relevant mitigation steps can be taken [4].

Transients refer to part of the change in waveform that disappears during transition from one steady state operating condition to another; and they can be classified as either impulsive or oscillatory transients.

Voltage Variations are caused by fault conditions and the energization of large loads, where high starting currents are involved. The faults can cause a 'drop', 'rise' and 'supply void' in the supply voltage, and are also known as sag, swell and interruptions respectively. Voltage sag is normally caused by system faults, energization of heavy loads and starting of large motors. Swells are usually associated with system fault conditions, but they are not as common as voltage sags.

Waveform Distortion is defined as a steady-state deviation from an ideal sine wave of line frequency principally characterized by the spectral content of the deviation. Harmonics; notching and noise are the major waveform distortions [5].

A signal can be represented in the frequency domain by its Fourier transform which is written as

$$F[k] = \frac{1}{N} \sum_{n=0}^{N-1} f[n] e^{-j(2\pi kn/N)}, k=0, 1, \dots, N-1.$$

where $f[n]$ is the discrete-time signal, $F[k]$ is its frequency domain representation [6].

Wavelet decomposition provides a way of analyzing a signal both in time and frequency domains. If we denote f as a function defined on the whole real line, then, for a suitably chosen mother wavelet function ψ , f can be expanded as

$$f(t) = \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} w_{jk} 2^{j/2} \psi(2^j t - k)$$

where the functions $\psi(2^j t - k)$ are all orthogonal to each other. The coefficient w_{jk} gives information about the behavior of the function f concentrating on the effects of scale around 2^{-j} near time $t \times 2^{-j}$. This wavelet decomposition of a function is closely related to a similar decomposition (the discrete wavelet transform, DWT) of a signal observed in discrete time [7, 8].

Frequency based analysis is very common, but it is not ideally suitable for transient analysis as time information is lost. For non-stationary signals wavelet analysis allows the use of long time intervals where we want more precise low-frequency information, and shorter regions where we want high-frequency information [7, 9, 10]. This is evident from Fig 1.

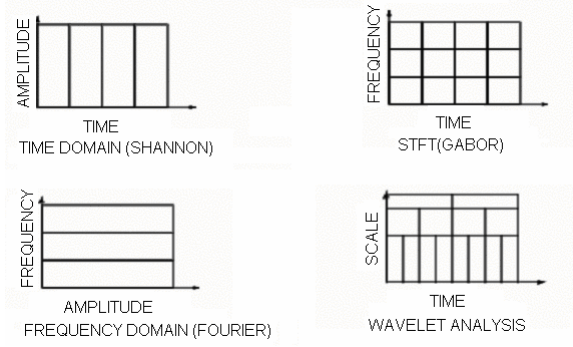


Fig 1. Signal Analysis Techniques.

Fourier transform is suitable for analyzing stationary signals and extracting spectrum components at specific frequencies while wavelet transform more adapts to dynamic signals and is appropriate for capturing time-localized short period phenomena [11]. Our considered data, range from very slow to very fast changing disturbances.

Various approaches for feature extraction have been proposed for classifying the power quality events. A comparatively recent research shows that this can be done in the wavelet domain by comparing the energies of different wavelet transform levels of the disturbance signal with that of a pure sinusoidal signal. The comparisons result in very easily recognizable patterns for different disturbance signals [12]. This method may experience difficulties in dealing with a wide range of real life recorded power disturbances. A combination of Fourier transform and wavelet transform works in a more efficient manner for feature extraction than either of these two alone.

Past researches have proven fuzzy logic (FL) as a powerful categorization tool [6, 13, 14]. Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multi-valued logic. But in a wider sense, which is in predominant use today, fuzzy logic is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree [9, 15].

This paper is organized in the following manner. Section 2 describes the procedure of feature extraction and disturbance categorization. Section 3 presents a case study conducted on a commercial site followed by analysis of a variety of disturbance waveforms which were recorded at other sites. The proposed system is built in MATLAB environment and tested using field-measured voltage waveforms.

2. DETECTION AND CATEGORIZATION OF POWER QUALITY EVENTS USING FUZZY LOGIC

2.1 Feature extraction

The following features inherent to different types of power quality events have been extracted using the corresponding formulas [6]:

1. Fundamental component. It will be large for Swells and small for Sags and Outages.

$$V_n = \sqrt{2} \text{abs}(V^n[1])$$

2. Phase Angle Shift.

$$PS_n = \text{angle}(V^n[1]) - \text{angle}(V[1])$$

3. Total Harmonic Distortion. It will be large for Harmonic disturbances.

$$THD_n = \sqrt{\sum_{k=2}^{\text{int}(N/2)} \{ \text{abs}(V^n[k]) \}^2 / V^1[1]}$$

4. Number of peaks of the Wavelet Coefficient. It will be large for Notches.

$$N_n = \text{peak}(\text{abs}(WC^n[k])), \text{ for all } k.$$

5. Energy of the Wavelet Coefficients. It will be large for Transients.

$$EW_n = \sum_{k=1}^{\text{leng}} \text{abs}(WC^n[k])$$

6. Oscillation number of Missing Voltage. It will be large for Transients.

$$OS_n = \text{root}(v_{\text{miss}}^s) \text{ where}$$

$$v_{\text{miss}}[i] = v[i] - (2/N) * \text{abs}(V^l[1]) * \cos\{ \text{angle}(V^l[1]) + 2\pi(i-1)/N \}$$

and v_{miss}^s is an array of $v_{\text{miss}}[i]$, $i = 0, 1, 2, \dots, L-1$.

7. Lower Harmonic Distortion. It will be large for Harmonic disturbances.

$$TS_n = \sqrt{\sum_{k=2}^{10} \{ \text{abs}(V^n[k]) \}^2 / V^1[1]}$$

8. Oscillation Number of RMS Variations, e.g. it will be large for Flickers.

$$RN = \text{root}(V_{rms}^s - \text{mean}(V_{rms}^s))$$

where V_{rms}^s is an array of V_{rms}^n which is defined as

$$V_{rms}^n = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} v^2[i + (n-1)N]}$$

- $V^n[k]$ is the Discrete Fourier Transform (DFT) for the samples contained in the n th data window and $V[k]$ is the DFT for the whole signal.
- WC^s is an array of $WC_n[k]$ for $k = 1, 2 \dots \text{length}$ where length is the length of $WC_n[k]$.
- n is the number of data windows.
- $v[i]$ represents the sampled input signal, $i = 0, 1, 2, 3, \dots, L-1$ where L is the length of the signal.
- N is the number of samples in one data window (one cycle).
- WC are the second level detail wavelet coefficients obtained by using Daubechies-4 wavelet.
- $\text{abs}(\cdot)$ gives the absolute value of the argument.
- $\text{angle}(\cdot)$ returns the phase angle of the input argument.
- $\text{int}(N/2)$ equals $N/2$ if N is even, and $(N-1)/2$ if N is odd.
- $\text{peak}(\cdot)$ returns the number of peaks of the argument.
- $\text{root}(\cdot)$ returns the number roots (zero-crossings) of the argument
- $\text{mean}(\cdot)$ returns the mean of the argument.

2.2 Categorization

A brief rule set for the fuzzy expert system is as follows:

- Rule 1: if V_n is A_4 and N_n is F_1 and OS_n is G_1 then IMPULSE.
- Rule 2: if V_{n+1} is A_5 and $\{PS_n$ is C_1 or PS_{n+1} is $C_1\}$ then SWELL.
- Rule 3: if V_{n+1} is A_2 or V_{n+1} is A_3 and $\{PS_n$ is C_2 or PS_{n+1} is $C_2\}$ then SAG.
- Rule 4: if V_{n+1} is A_3 and N_n is F_2 and OS_n is G_2 then NOTCH.
- Rule 5: if RN is K_1 then FLICKER.
- Rule 6: if THD_n is B_2 and THD_{n+1} is B_2 and THD_{n+2} is B_2 then HARMONIC.

- Rule 7: if V_n is A_1 or V_{n+1} is A_1 then OUTAGE.
- Rule 8: if V_n is A_6 and V_{n+1} is A_6 then SWELL
- Rule 9: if OS_{n+1} is G_2 and THD_n is B_2 and EW_n is D_1 then TRANSIENT.
- Rule 10: if $\text{root}(v^s) > (2 * \text{no. of cycles recorded})$ then PROBLEM FOR SWITCHING DEVICES.

IMPULSE, SWELL, SAG, NOTCH, FLICKER, HARMONIC, OUTAGE, and TRANSIENT are fuzzy variables which represent the degree (membership) to which a particular power quality event belongs to these categories. A higher membership value implies that a particular disturbance is more dominant in the test waveform. A_i , B_i , C_i , D_i , F_i , G_i , H_i , and K_i are the membership functions for the inputs which are obtained from the eight extracted features. Triangular and trapezoidal membership functions are used.

3. CASE STUDY AND RESULTS

The supply panel for a Baggage Handling System at a site in Brisbane was monitored for power disturbances. The equipment used was the BMI 8010 PQNode, developed by Basic Measuring Instrument (BMI) of Santa Clara, California in conjunction with Electrotek Concepts Inc[16]. The BMI 8010 PQNode can be set to stand-alone operation at the selected site to perform power quality monitoring. Communication between the PQNode and a computer is via a RS-232 link. Following is a case study based on the power quality data recorded by the BMI 8010 PQNode [17].

3.1 Transients in the network

At the monitored site, majority of the loads were induction motors and variable speed drives. During the monitoring period of a week only three wave faults were recorded which included oscillatory transients (Fig.2, 3 & 4).

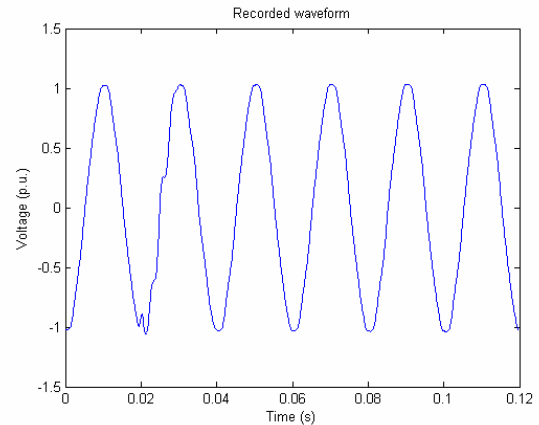


Fig 2. Recorded wave fault.

These transients occurred between 7am to 8am on three different days. This is because at these times there is more traffic on the belts and to compensate for that, more number of belts is brought into action. When these conveyor belts are put on, voltage sags are found because these belts are run by induction motors.

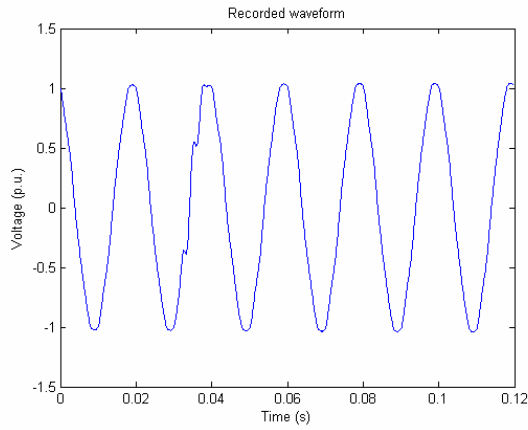


Fig 3. Recorded wave fault

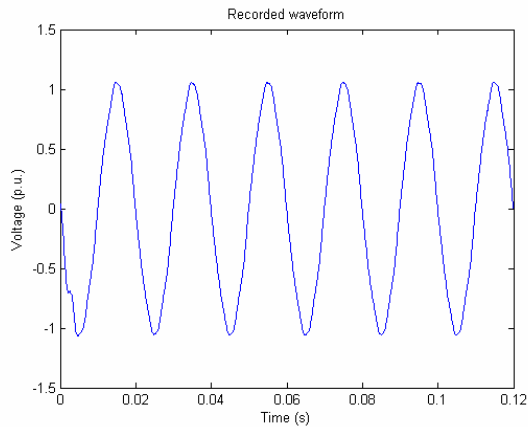


Fig 4. Recorded wave fault

PQNode was not able to register these sags because:

1. The location where the voltage sag took place was quite far away from the monitoring location.
2. The sags are sensed and corrected quickly by the capacitor banks which are located at various locations in the network.

As a result PQNode only captured the oscillatory transients which were possibly caused by the switching of capacitor banks.

3.2 Harmonics in the network

The Total Harmonic Distortion (THD) was found to be within the safe limits (Australian Standards AS 2279) for all days except one when THD was recorded to be 6.571% (Fig.5) which is above the allowed limit of 5%. According to the Maintenance Coordinator the generators were run on this day as a routine exercise

to maintain the reliability of the generators. The excessive harmonics show up in the voltage because when the generators are connected to the network it changes the overall impedance parameters of the network. This change is evident because the change in parameters took place locally and not at a distant point, as it happens when generators are connected or disconnected to the power grid.

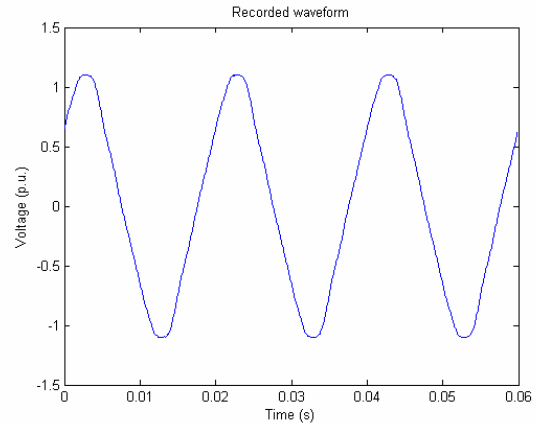


Fig 5. Recorded waveform

3.3 Phase unbalance

The following figure shows that the neutral has a continual current between 12A to 50A. The irregular current trend observed could be due to an imbalance in the phases (Fig. 6)

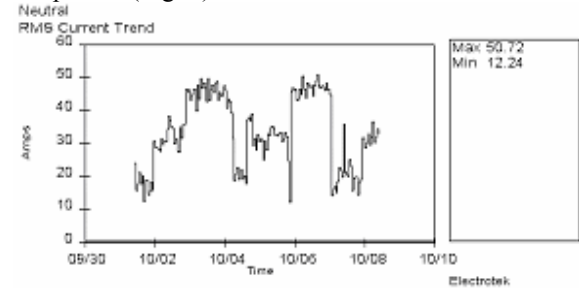


Fig 6. Irregular Neutral current.

The single-phase waveforms in Figs.2, 3, 4, and 5 were analyzed using the proposed method and the results have been listed in Table 1.

| EVENTS | Fig2 | Fig3 | Fig4 | Fig5 |
|-----------|------|------|------|------|
| IMPULSE | 0 | 0 | 0 | 0 |
| SWELL | 0 | 0 | 0 | 0 |
| SAG | 0 | 0 | 0 | 0 |
| NOTCH | 0 | 0 | 0 | 0 |
| FLICKER | 1 | 0 | 0 | 0 |
| HARMONIC | 0 | 0 | 0 | 1 |
| OUTAGE | 0 | 0 | 0 | 0 |
| TRANSIENT | 1 | 1 | 1 | 0 |

Table 1. Analysis results

For example, it shows that the waveform in Fig 2 has a Flicker as well as a Transient in it because the fuzzy variables TRANSIENT and FLICKER are each equal to one. Similarly the waveform in Fig 5 has a harmonic problem as the fuzzy variable HARMONIC is equal to one.

3.4 Other recorded disturbance waveforms.

Some voltage waveforms which were recorded at other sites are given in Figs 7-10. These are only a few of the waveforms which were used to build the proposed system. These waveforms are different and not observed in Sections 3.1-3.3.

The events and their respective membership values corresponding to Figs 7-11 are given in Table 2.

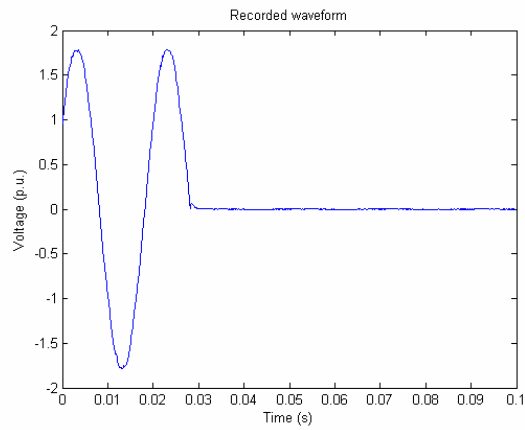


Fig 7. Recorded waveform

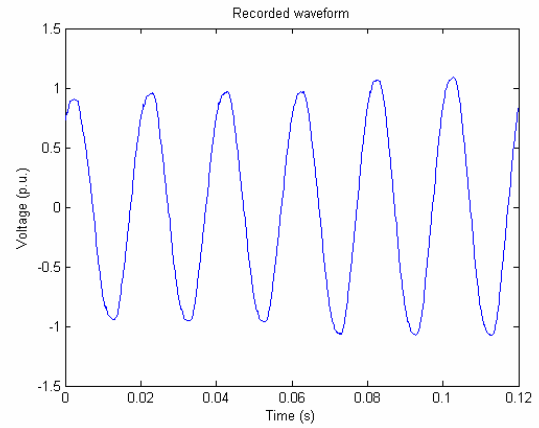


Fig 9. Recorded waveform

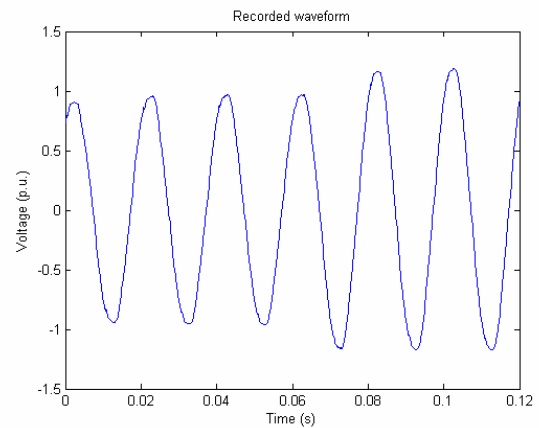


Fig 10. Recorded waveform

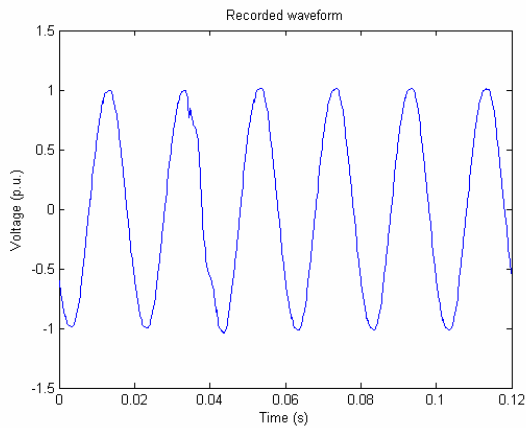


Fig 8. Recorded waveform

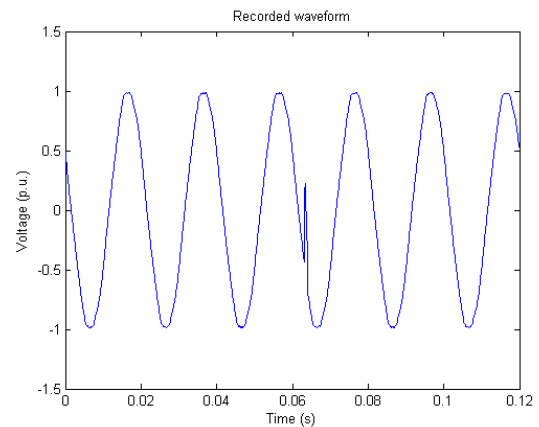


Fig 11. Recorded waveform

| EVENTS | Fig7 | Fig8 | Fig9 | Fig10 | Fig11 |
|-----------|------|------|------|-------|-------|
| IMPULSE | 0 | 0 | 0 | 0 | 1 |
| SWELL | 1 | 0 | 0.15 | 1 | 0 |
| SAG | 0 | 0 | 0.05 | 0 | 0.07 |
| NOTCH | 0 | 1 | 0 | 0 | 0 |
| FLICKER | 0 | 0 | 0 | 0 | 0 |
| HARMONIC | 0 | 0 | 0 | 0 | 0 |
| OUTAGE | 1 | 0 | 0 | 0 | 0 |
| TRANSIENT | 1 | 1 | 0.05 | 1 | 1 |

Table 2. Analysis results

A typical example of a membership greater than zero but less than one, is Fig 9. It is evident from the membership values for SWELL, SAG and TRANSIENT that there is a disturbance in the waveform of small magnitude but it cannot be neglected because our rule set has been designed such that it detects every possible disturbance. In this case SAG, which has the maximum value of membership, is the disturbance present in this waveform. In a similar way results have been obtained for various recorded waveforms.

4. CONCLUSIONS

This paper presents a practically efficient tool for power quality data analysis and categorization. The method uses Fourier transform, wavelet techniques and fuzzy set rules to identify power quality problems with minimal errors. The proposed method has been implemented for analysis and categorization of power quality data collected from various measurement sites in Brisbane, Australia. Simulation results are given in the paper to illustrate the effectiveness and robustness of the proposed method in power quality categorization applications. More work is currently in progress to validate the proposed tool, which will be reported in near future.

5. REFERENCES

- [1] R. C. Dugan, M. F. McGranaghan, and H. W. Beaty, *Electrical power systems quality*. New York: McGraw Hill, 1996.
- [2] M. H. J. Bollen, IEEE Industry Applications Society, IEEE Power Electronics Society, and IEEE Power Engineering Society, *Understanding power quality problems : voltage sags and interruptions*. New York: IEEE Press, 2000.
- [3] W. W. Dabbs, D. D. Sabin, T. E. Grebe, and H. Mehta, "Probing power quality data," *IEEE Computer Applications in Power*, vol. 7, pp. 8-14, 1994.
- [4] P. F. Ribeiro and D. A. Rogers, "Power electronics, power quality and modern analytical tools: the impact on electrical engineering education," in *Proceedings. Frontiers in Education. Twenty Fourth Annual Conference*, L. P. Grayson, Ed., 1994, pp. 448-451.
- [5] L. W. Cheok, T. K. Saha, and Z. Y. Dong, "Power quality investigation with wavelet techniques," presented at AUPEC 2002, Melbourne, Australia, 2002.
- [6] M. Kezunovic and Y. Liao, "A novel software implementation concept for power quality study," *IEEE Transactions on Power Delivery*, vol. 17, pp. 544-9, 2002.
- [7] Y. F. Low and Z. Y. Dong, "Enhancing Neural Network Electricity Load Forecast with Wavelet Techniques," presented at ASCC 2001, Singapore, 2001.
- [8] B. N. Tran, T. M. Nguyen, and M. M. Shihabi, "Wavelets," J. Webster's Wiley Encyclopedia of Electrical and Electronics Engineering ed: John Wiley & Sons Inc., 1999.
- [9] "Matlab Help files," Matlab 6.0.
- [10] A. Al Rawi and M. Devaney, "Wavelets and power system transient analysis," in *IEEE Instrumentation and Measurement Technology Conference*.: IEEE, New York, NY, USA, 1998, pp. vol.2, 1331-1334.
- [11] I. Daubechies, "The wavelet transform, time-frequency localization and signal analysis," *IEEE Transactions on Information Theory*, vol. 36, pp. 961-1005, 1990.
- [12] J. W. Resende, M. L. R. Chaves, and C. Penna, "Identification of Power quality disturbances using MATLAB wavelet transform toolbox," 2001.
- [13] S. Santoso, E. J. Powers, W. M. Grady, and A. C. Parsons, "Power quality disturbance waveform recognition using wavelet-based neural classifier. I. Theoretical foundation," *IEEE Transactions on Power Delivery*, vol. 15, pp. 222-228, 2000.
- [14] W. R. Anis Ibrahim and M. M. Morcos, "Artificial intelligence and advanced mathematical tools for power quality applications: a survey," *IEEE Transactions on Power Delivery*, vol. 17, pp. 668-673, 2002.
- [15] J. Yen and R. Langari, *Fuzzy logic : intelligence, control, and information*. Upper Saddle River, N.J.: Prentice Hall, 1999.
- [16] E. C. Inc., "Electrical Power Systems Quality," <http://www.electrotek.com>, 2003.
- [17] B. M. Instruments(BMI), *PQ Node User's Manual*, 2 ed: Basic Measuring Instruments, Santa Clara, California, USA, 1993.